MEDD

Best Practice Guide

Version: 13-05-2015

Authors

Lucas, P. (VSL)
Snijder, R.A. (UMC Utrecht)
Timmerman, A.M.D.E. (UMC Utrecht)
Batista, E. (IPQ)
Bissig, H. (METAS)
Ogheard, F. (CETIAT)

The research leading to the results discussed in this report has received funding from the European Metrology Research Programme (EMRP). The EMRP is jointly funded by the EMRP participating countries within Euramet and the European Union.

Index

1 Introduction

In a Dutch study it is shown that 40% of the adverse incidents can be avoided [1]. Although a small percentage of these incidents are believed to be caused by infusion technology [2], this concerns a great number of patients because 90% of all hospitalized patients receive some kind of infusion [3].

This best practice guide concerns various aspects related to infusion technology and is developed for clinical users such as nurses and physicians. However all others involved in infusion technology, including clinical supervisors and medical technicians, are also encouraged to read this guide. In Figure 1 all parties are shown that are involved in infusion technology. The clinicians have a key role in ensuring the patients receive the correct dosage over time. Note, one could argue notified bodies should also be included in the figure. However, because (international) accreditation is not common for infusion technology this party has been omitted.

This guide is put together based on a literature research and on lessons learned from a recent European research project [4], which focused on critical drug delivery applications. Here, critical is defined as those applications that require an accuracy of 95% or better. The technical aspects covered in this guide are therefore mostly related to how this accuracy can be ensured. Because the focus is at high accuracy applications, only syringe pumps are considered.

This guide is divided into two sections. Section 1 concerns the non-technical aspects related to safe and sound infusion therapy and are based on the literature survey, i.e. best practices for clinical users. It contains aspects such as hygiene, incidents, alarms, etc. Section 2 concerns the technical aspects related to safe and sound infusion. It contains aspects such as delays (in startup or changing flow rates), compliance and the potential interaction when multiple pumps are infusing through one injection point. This section is based on the research carried out in the aforementioned project.

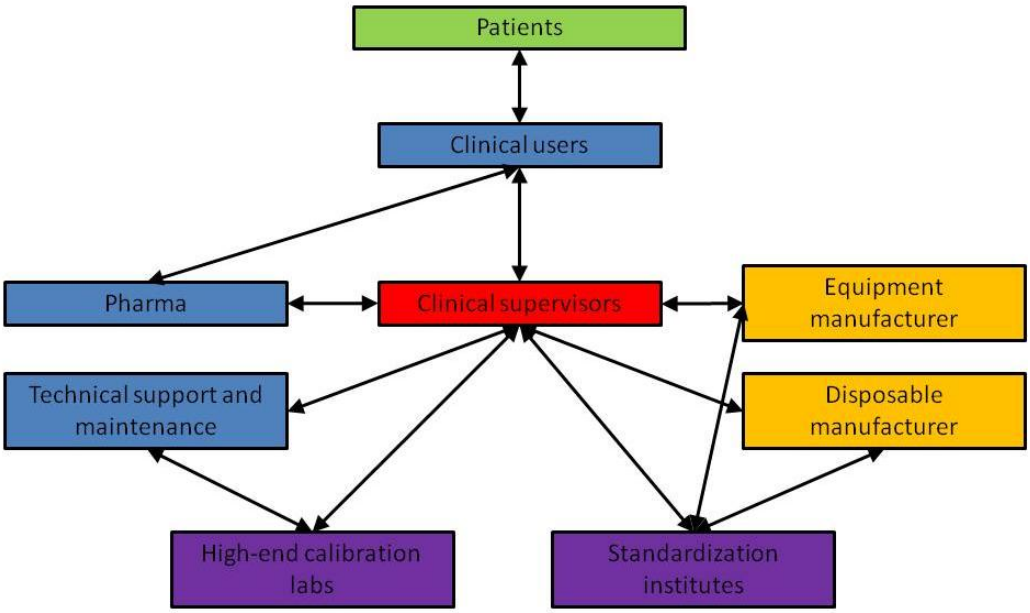

Figure 1 Parties involved in infusion technology. The clinical users and clinical supervisors have a key role in ensuring the patients receive a correct dosage.

2 Non-technical aspects

Over the course of the last years, a risk analysis has been conducted to assess the highest infusion risks and their respective preventive measures. To obtain best practices from other hospitals, also a survey of best practices has been disseminated online [5]. Using this survey, best practices from multiple hospitals (distributed over several European countries) have been acquired. In this section these best practices are shortly discussed, accompanied by some general guidelines. Please note that each hospital has specific protocols and guidelines regarding the usage of infusion technology and clinicians should be familiar with these protocols, or at least know where to find them.

General recommendations:

- Hospitals should appoint an infusion commission for the development and maintaining of infusion protocols.
- Clinicians should be informed on how and where to find infusion protocols.
- Integrate protocols as much as possible.
- Consider using new technology such as, smart pump technology, bar code scanners, standard pharmaceutical concentrations etc. However, note that new technology will not always improve the safety in every situation.
- Development of a system in which protocols can be easily found.

2.1 Education

When new equipment (including disposables) is introduced, training should be given. Preferably the training is given by the manufacturer or someone who was trained by the manufacturer. Education should at least include training on usage of the pump application ("button training"), preventing free flow, adequate set up of the infusion system of pumps and disposables, alarm training and, if applicable, use of the dose error reduction software.

It is recommended to repeat education on the usage of infusion technology with an appropriate interval, depending on the complexity of the infusion application and equipment renewals and software updates. Apart from device application training, infusion training should also include training on intravenous medication preparation by certified pharmacists and training on vascular access by infusion therapy specialists. From the survey it was found that written protocols could not always be found by the clinician (physical or digital copy). Therefore, education regarding infusion therapy should also inform the clinical users on where to find the protocols concerning the entire infusion process.

2.2 Hygiene

Infection risk is one of the highest overall risks of infusion therapy. Although standard nursing training includes lessons on hygiene it cannot be emphasized enough to keep disposables sterile. Sepsis is still a very common complication on intensive care units [6]. Therefore, it is recommended to have regular retraining and to use instructional videos. Further, it is recommended that doctors and nurses get the same training. Moreover, it is obligatory to wash hands before any patient interaction and keep the infusion and disposables sterile.

Hand hygiene, personal hygiene, general precautions, disinfection of materials and preventing person to person infections are important considerations for all clinicians, as well as other personnel working in the hospital. Follow your standard hospital and government health protocols. A mistake often made is not waiting long enough to let the alcohol dry when disinfecting hands or devices. From evidence based sources it is recommended to wait 30 seconds for the alcohol to dry [7].

2.3 Clinical process description

2.3.1 Arrival patient on department

General recommendations when a patient arrives in the hospital:

- Check Medication.
- Check Patient.
- Check Hypersensitivity.
- Medication systems should be checked and double checked. Is the right patient being treated with the right infusion therapy?

2.3.2 Medication policy and preparation

General recommendations for double check procedures regarding medication preparation (to be performed by a second person) [8]. The following checks are recommended:

- Take infection prevention and hygiene into account.
- Check with the parental protocols for specific usage of medication.

Materials:

- Correct medication order?
- Correct pharmaceutical?
- Correct concentration?
- Expiration date?
- Correct diluents (if applicable)?
- Correct amount of diluents (if applicable)?
- Correct preparation method?

Preparation of medication:

- Correct administration label?
- Discoloration / clouding / crystallization?
- Keep in dark and cool location.

2.3.3 Apply infusion to patient

General recommendations to apply infusion to a patient:

- Choose the correct route of administration.
- Choose the correct vascular access device.
- Take special care to keep vascular access devices sterile.

Extravasation is a potentially dangerous incident in which the medication is wrongfully infused outside of the blood vessel, which may lead to necrosis. The following general guidelines can be followed to recognize and prevent extravasation [9].

Prevent extravasation:

- Check prior to starting IV-administration if blood is flowing back into the IV system (passive backflow).
- Ask the patient to report possible pain or swelling.
- Check the patient regularly during infusion therapy.
- Keep the vascular access point visible as much as possible.
- The risk of extravasation is increased after a difficult vascular access insertion procedure. Consider to redo the insertion in case of doubt.
- React adequately on occlusion alert

Recognizing extravasation:

- Discoloration of the skin: red, pale, splotchy.
- Swelling of the skin.
- Temperature of the skin: colder or warmer.
- Tingling loss of sense of the skin.
- Pain / burning sensation of the skin.
- Decrease in flow or abrupt stopping of infusion.
- Leakage of the vascular access site.

Refer to your local protocols, physicians and supervisors for the action to be taken in case of extravasation.

2.3.4 Administering medication and monitoring

Critical medication typically includes medication with narrow therapeutic ranges, that is where the values of the working and toxic concentration are close to one another. Because the risk of over and under dosing is considerable, the technical difficulties of infusion devices, discussed in Chapter 3, should be taken into consideration. Furthermore, in cases of critical blood regulating medications, i.e. inotropics, blood pressure, heart rhythm and ECG should be monitored [10]. Critical medications should have specific safety protocols, refer to these protocols for guidelines on specific (parenteral) medications.

Changing syringes and preventing free flow

When syringe change has to be performed during infusion therapy, it is very important to clamp the infusion line. If an infusion line is not clamped correctly during the syringe change, free flow may occur. Especially when the syringe is outside the pump and the patient is situated below the syringe (i.e. there is a height difference) the syringe may empty into the patient causing an adverse event.

The following procedure is recommended when a syringe is changed:

- If the syringe is outside the pump clamp the infusion line.
- Check if the line is damaged (i.e. due to previous clamps).
- Remove the clamp *directly* after the syringe is correctly placed and secured in the pump.
- Change the pump in case the syringe is repeatedly not recognized.

Alarms

Alarm fatigue can be described as not noticing a serious alarm amongst the constant issuing of less serious alarms. Research has shown that infusion users may not notice every alarm. Differentiation between the types of alarms could therefore be considered, though this technique is still being developed. At this time, users should be aware that it is possible to miss infusion pump alarms because of alarm fatigue. In addition, it is recommended not to change the occlusion sensitivity recommended by the infusion committee or technical department without the advice of technicians and pharmacists.

Incidents

Just as any medical technology, incidents may be caused by malfunction of the infusion pumps. In such a case, the following general recommendations are given [11]:

- If unusual operation of infusion pumps is observed, that cannot be restored by the clinician, it should be considered to stop the treatment based on the condition of the patient. If the patient requires emergency treatment of stopping the treatment is too risky, the treatment should be continued.
- In case of an incident with infusion pumps it should be isolated and not be re-used.
- After malfunction of infusion pumps, a qualified technician should be consulted.
- An adequate report should be handed over together with the pump in which the defect has occurred. Moreover, all incidents such as extravasation or medication errors should be reported as adverse events.
- It is recommended to analyze trends in incident with medical technology. Therefore, it is important to report these incidents with sufficient details in a uniform matter in the entire hospital.

We recommend to consider the following flow chart given in Figure 2 in case of a technical incident [11].

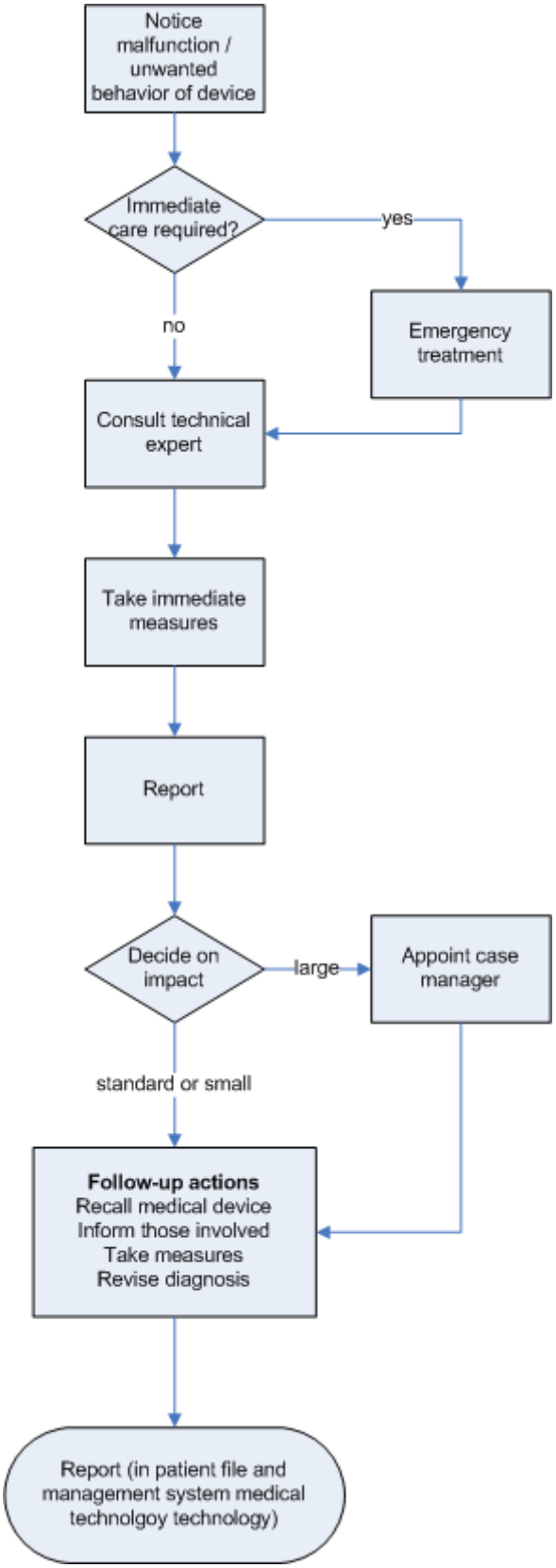

Figure 2 Recommended procedure in case of a technical incident

3 Technical aspects

In this section the technical aspects of the collected best practices are discussed. The following topics are discussed. In Section 3.1 the response time of single pump infusion is discussed, whereas in Section 3.2 the dosing accuracy is discussed. Next, in Section 0 the response behavior and dosing accuracy of multiple pump infusion is discussed. Finally, in Section 3.4 it is briefly discussed how infusion pump setups can be tested and calibrated, whereas in Section 3.5 a brief summary and recommendations are given.

3.1 Response time for single pump infusion

When a pump is started, or when the infusion rate is changed, it may take a while before the new set point is reached. Even when the infusion line is pre-filled, the startup delay (also called delayed onset) can be dramatically, especially when a narrow catheter or cannula is used. In Figure 3 an example of a startup delay is shown; only after 1 hour the flow reaches 95% of its target value.

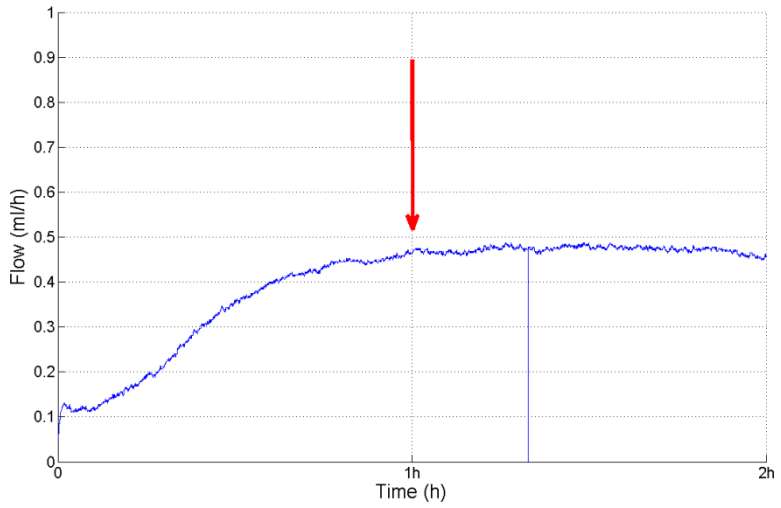

Figure 3 Startup delay; the red arrow indicates when the flow rate has reached 95% of its target.

This delay in response time[1] is caused by the compliance, or flexibility, of the system (defined as the volume increase for a unit increase in pressure). Typically when an infusion pump is started, or when the flow rate is increased, the line pressure increases (the pump 'pushes harder on the fluid'). Because of the flexibility of the system, this pressure increase will cause the syringe, infusion line and potential accessories to expand (the internal volume increases). Hence, initially the infusion fluid is not delivered to the patient, however used to inflate the syringe, infusion line and potential accessories.

In Figure 4 startup delays for various syringes, pumps and accessories are shown (infusion line and filter). From this figure it follows that start up delays in general increase with decreasing flow rate. (Remark, the much larger startup delay shown in Figure 3 is due to a high flow resistance and high

[1] Response time refers to a startup delay (or delayed onset) or a delay in reaching the new set point after it has been modified.

back pressure of infusion in an artery.) Next, in Table 1 the measured compliance is given for various accessories and pump B (the larger the compliance, the larger the startup delay). From this table it follows the syringe has the largest impact on the compliance of the complete setup. Further, the measured compliance given in Table 1 shows from the accessories long infusion lines and a filter have the largest impact on the compliance. However, from Figure 4 it follows the measured startup delay does not always follow a clear trend, for example adding a filter or infusion line lowers the startup time for 'Syringe 1'. This is probably caused by the significant spread in measurement results, i.e. repetitions of exactly the same test could result in significant different results (as also found in the literature [12].

Similarly as the startup delay, there will also be a delay when the flow rate is changed. In Figure 5 the response time is shown as function of the flow rate, for a 10 and 50 ml syringe and for doubling and quadrupling the flow rate. Similarly as for the startup time, the response time increases with decreasing flow rate. From this figure follows the response time for quadrupling is lower than for doubling the flow rate. If one assumes the pump quickly reaches the new target flow rate, this behavior is in line with the earlier observations: the lower the flow rate, the higher the startup time.

Table 1 Compliance ('flexibility') of a drug delivery system including accessories and two different syringe volumes.

Scenario	compliance complete setup using a 10 ml syringe (ml/bar)	compliance complete setup using a 50 ml syringe (ml/bar)
rigid syringe	0.24	N/A
standard syringe	0.21	1.54
standard syringe, 1.5m infusion line	0.20	1.54
standard syringe, 1.5m infusion line, entrapped air	0.22	1.61
standard syringe, 5.5m infusion line	0.44	1.89
standard syringe, filter	0.52	2.10
standard syringe, check valve	0.22	1.54

In general, the impact of varying operating conditions has a significant impact on the startup delay and response time. The range of operating conditions tested is:

- Viscosity; viscosity of water up to 4 times the viscosity of water.
- Back pressure, 24 mbar (roughly equivalent to the back pressure of a vein) and 170 mbar (roughly equivalent to 1-2 times the mean arterial pressure in an adult).
- Temperature; 10 degrees Celsius up to 30 degrees Celsius (steady state, no temperature gradients).

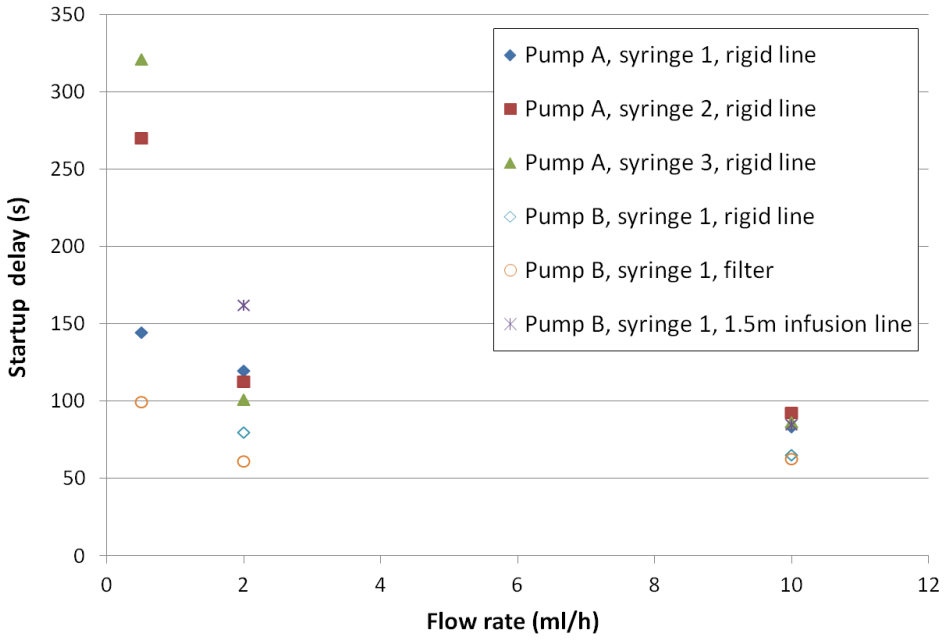

Figure 4 Startup delay for various syringes and two different accessories. All syringes have a volume of 50 ml.

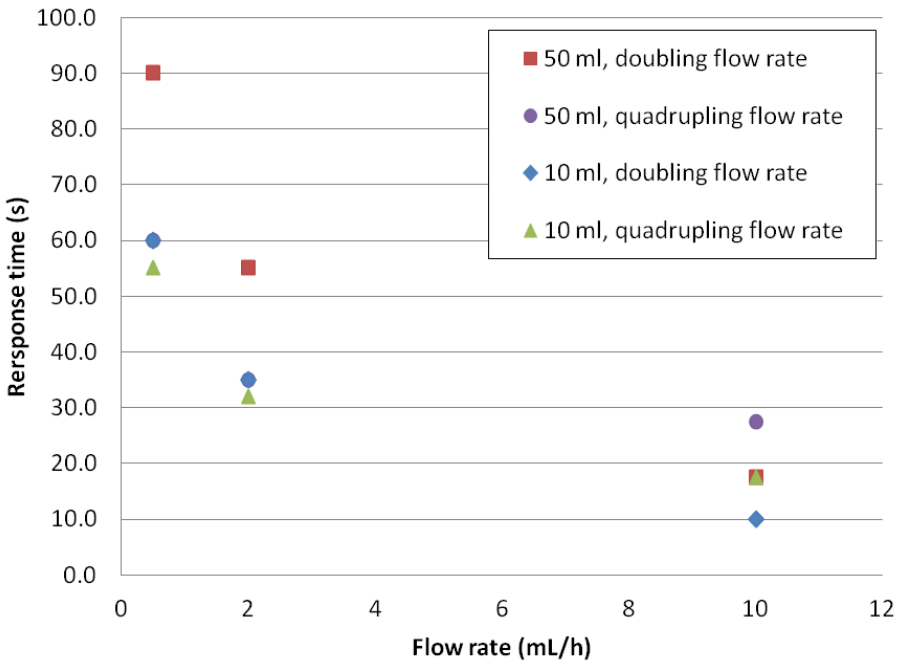

Figure 5 Delay in response time in doubling or quadrupling the flow rate.

From these measurements it followed varying operating conditions have the most pronounced impact in case a 50 ml syringe is used (which is consistent with the literature [13][14][15][16] [17]. In Figure 6 the impact of the back pressure and temperature are shown. The impact of viscosity on the startup delay did not have a significant impact for the conditions tested.

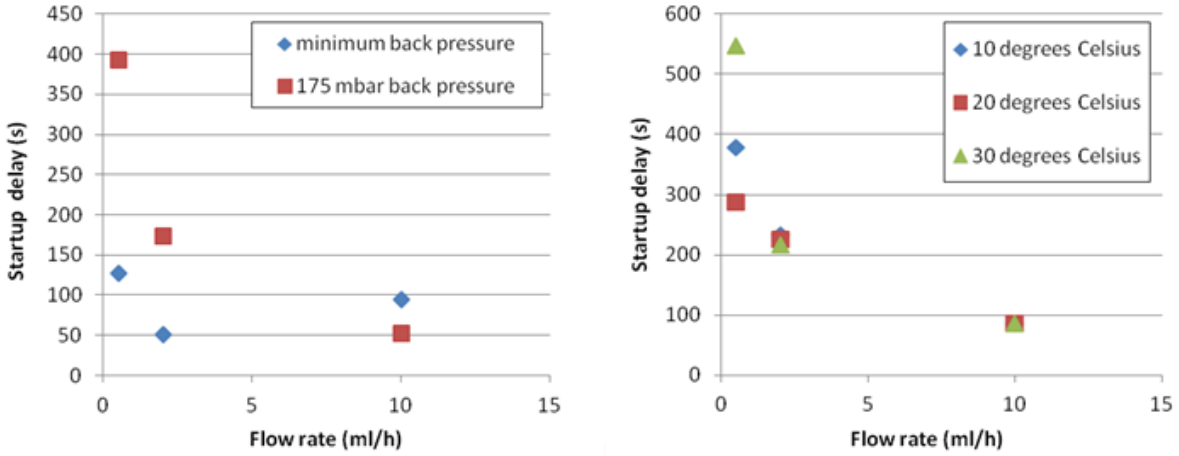

Figure 6 Impact of back pressure (left) and temperature (right) on the startup delay for a syringe pump with a 50 ml syringe and no additional accessories.

In order to minimize the startup delay (for low flow rates) one can use low compliance (rigid) infusion components (especially syringes). Alternatively, one can use small volume (e.g. 10 ml) syringes. Remark, small volume syringes are not advised for 'large' flow rates as this would require often replacements.

3.2 Dosing accuracy single pump infusion

In Section 3.1 the startup delay has been discussed; due to the compliance of the system it takes a while before the target infusion rate is reached. Hence, during the startup phase the flow rate error is significant and may be required to be taken into account. However, also during normal operation (significant) flow rate errors can occur, for example the syringe or the syringe pump may be imperfect. Here, normal operating conditions imply after the startup phase, a temperature of 20 degrees Celsius, near zero back pressure and water as the administered drug.

The relative flow rate is determined by:

$$\varepsilon = 100\% \frac{q_{pump\ set\ point} - q_{actual}}{q_{actual}}$$

where $q_{pump\ set\ point}$ is the target flow rate set in the pump and q_{actual} follows from the balance measurements. Therefore, a positive error means $q_{pump\ set\ point} > q_{actual}$, or, the set point is larger than the actual flow rate. Hence, the pump is delivering less than its set point. Similarly, for a negative error the pump is delivering too much. In Section 3.4.2 it is discussed how the flow rate error can be determined.

In Figure 7 to Figure 9 the flow rate error during normal operation conditions is shown for two different pumps and a syringe of 10 ml (only pump 1) and a 50 ml syringe. The bars given in Figure 7 and Figure 9 are the 'uncertainty of the calibration' per flow point. This uncertainty follows from the uncertainty in reference flow rate and the spread in the measurement results. The uncertainty in the reference flow rate is amongst others the result of resolution, variations in operating and environmental conditions, noise and nonlinearity of the balance. The true error is within the uncertainty bar with a confidence of 95%. The flow rates tested are 0.5 ml/h, 2 ml/h and 10 ml/h. In

the figures the flow rates have been given an artificial offset to visualize the results. As an example, the last series of measurements are all for a flow rate of 10 ml/h.

From Figure 7 and Figure 8 it follows that the measured flow rate error is between -2 and +2 % for pump 1 and between 2 ml/h and 10 ml/h. However, for a flow rate of 0.5 ml/h the measured errors are larger and also the spread is larger. Because of the measurement uncertainty it cannot be stated whether or not the pump is functioning within the 2% error bandwidth (which is a typical criterion used by manufacturers). This is because the true error can be anywhere within the given range [18] (uncertainty bar) (95% confidence level). Hence, the maximum *possible* error is given by the measured error plus the uncertainty (95% confidence level).

From Figure 7 it can be concluded the maximum possible error never exceeds 5% for a 10 ml syringe (95% confidence level) and pump 1. From Figure 8 it follows the errors are typically within the 5% error bandwidth (95% confidence level) for pump 1. However, in exceptional cases the maximal possible error can be as large as 7% (95% confidence level), see Figure 9. By comparing Figure 7 to Figure 9 it follows the errors and spread are larger for the larger syringe, especially for the lower flow rates, which is in accordance with the literature [13][17][14][15][16]. The spread in the measurement results is an artifact of the disposable syringe system because this spread is much smaller when more rigid syringes are used.

The flow rate stability has also been studied, however was found to be insignificant compared to the measurement spread. In other words, the flow rate instability is typically smaller than the variations between syringes and tests. Finally, following the measurements performed, the impact of varying operating conditions is in general limited on the flow rate accuracy. The range of operating conditions tested is:

- Viscosity; viscosity of water up to 4 times the viscosity of water.
- Back pressure, 24 mbar (roughly equivalent to the back pressure of a vein) and 170 mbar (roughly equivalent to 1-2 times the mean arterial pressure in an adult.).
- Temperature; 10 degrees Celsius up to 30 degrees Celsius (steady state, no temperature gradients).

For this range of test conditions, the following observations were made:

- The temperature and viscosity do not noticeably influence the flow rate error. There are variations in the measured flow rate; however these variations are not significant when the measurement uncertainty is taken into account.
- For the 10 ml syringe tested, an increased back pressure did not affect the delivered flow rate accuracy. However, for the 50 ml syringe tested, a back pressure of 170 mbar, the flow rate accuracy was slightly affected (up to 1.5 percent point). Nevertheless, the syringe pump kept functioning within the 5% bandwidth (95% confidence level).

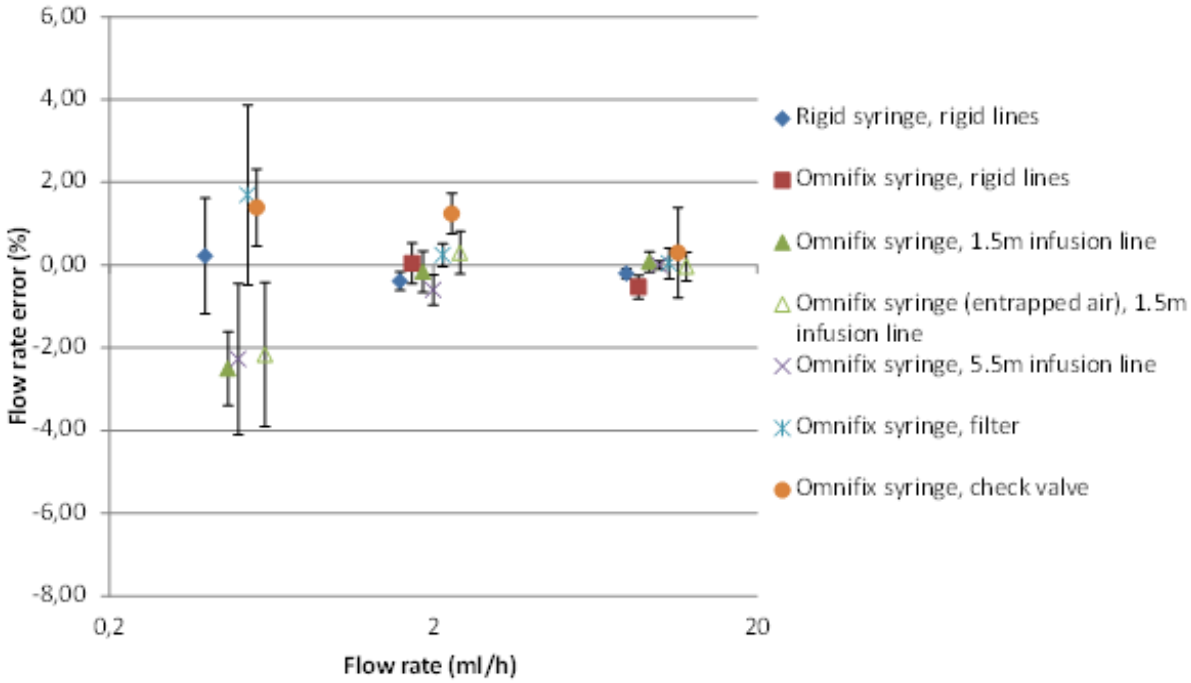

Figure 7 Flow rate error pump 1 during normal operation and steady operating conditions (10 ml syringe).

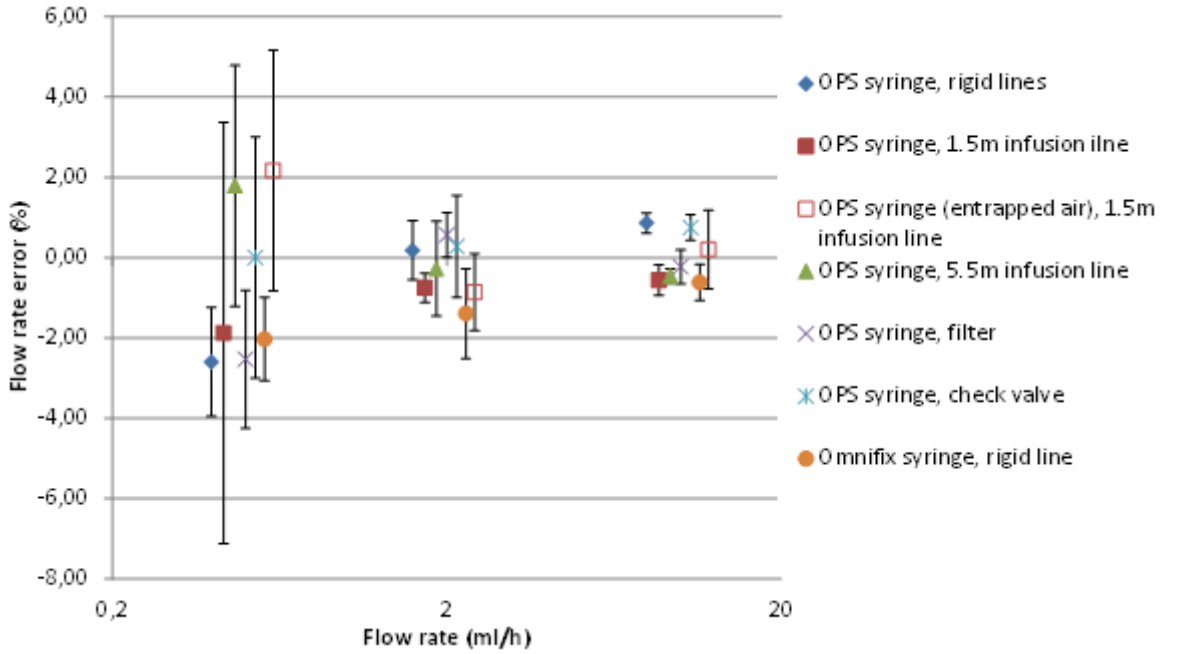

Figure 8 Flow rate error pump 1 during normal operation and steady operating conditions (50 ml syringe).

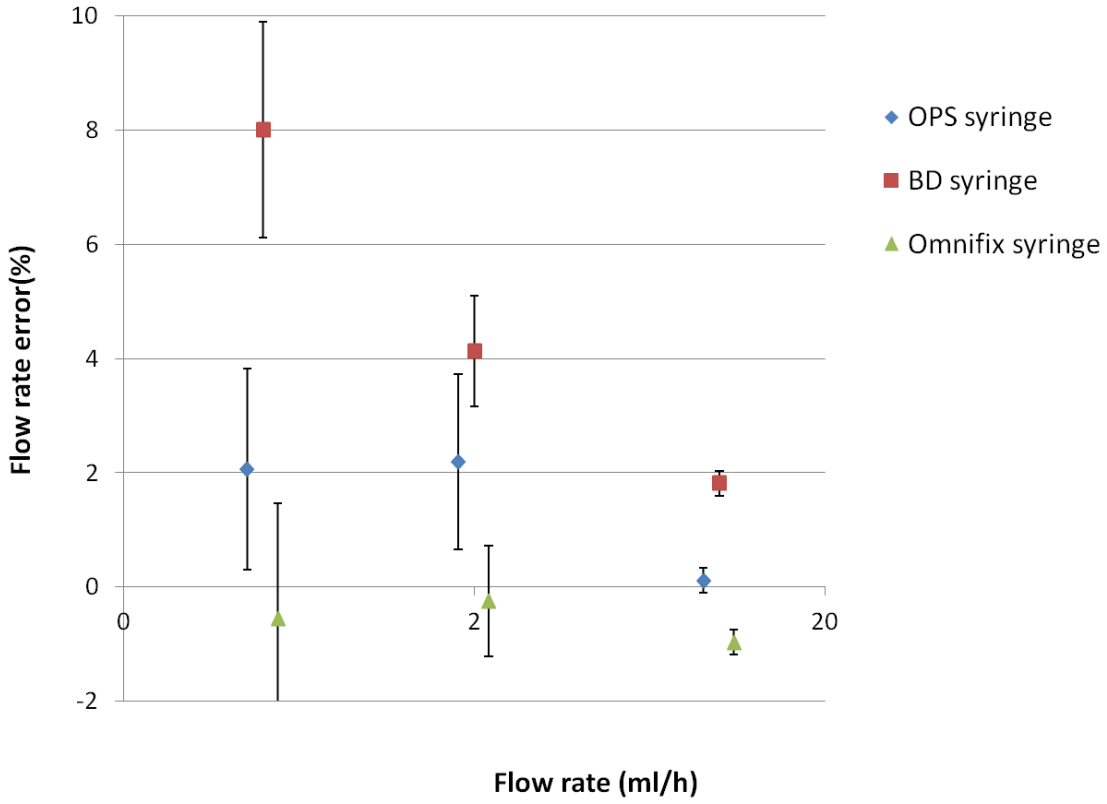

Figure 9 Flow rate error pump 2 during normal operation and steady operating conditions (50 ml syringe).

3.3 Dosing accuracy multiple pump infusion

Similarly as for single pump infusion, compliance will result in startup delay for a multiple pump setup. And also similarly as for single pump infusion there can be infusion rate errors due to imperfect syringes, syringe pumps and influence of operating conditions. However, when using multiple pumps, which all are all administrating some drug via the same injection point two other effects that will cause a delay or (temporal) offset in the target infusion (concentration). These two effects are the 'dead volume' and interaction between pumps.

The dead volume is the total volume between the mixing and injection point. Therefore, every particular mixture of drugs will need to travel through this volume before it reaches the patient. Consequently, in case the flow rate of one particular pump is changed, it will take some time before this new concentration (mixture) is felt by the patient. In other words, the mixture administered in the past first needs to travel through this dead volume. These phenomena are illustrated in Figure 10.

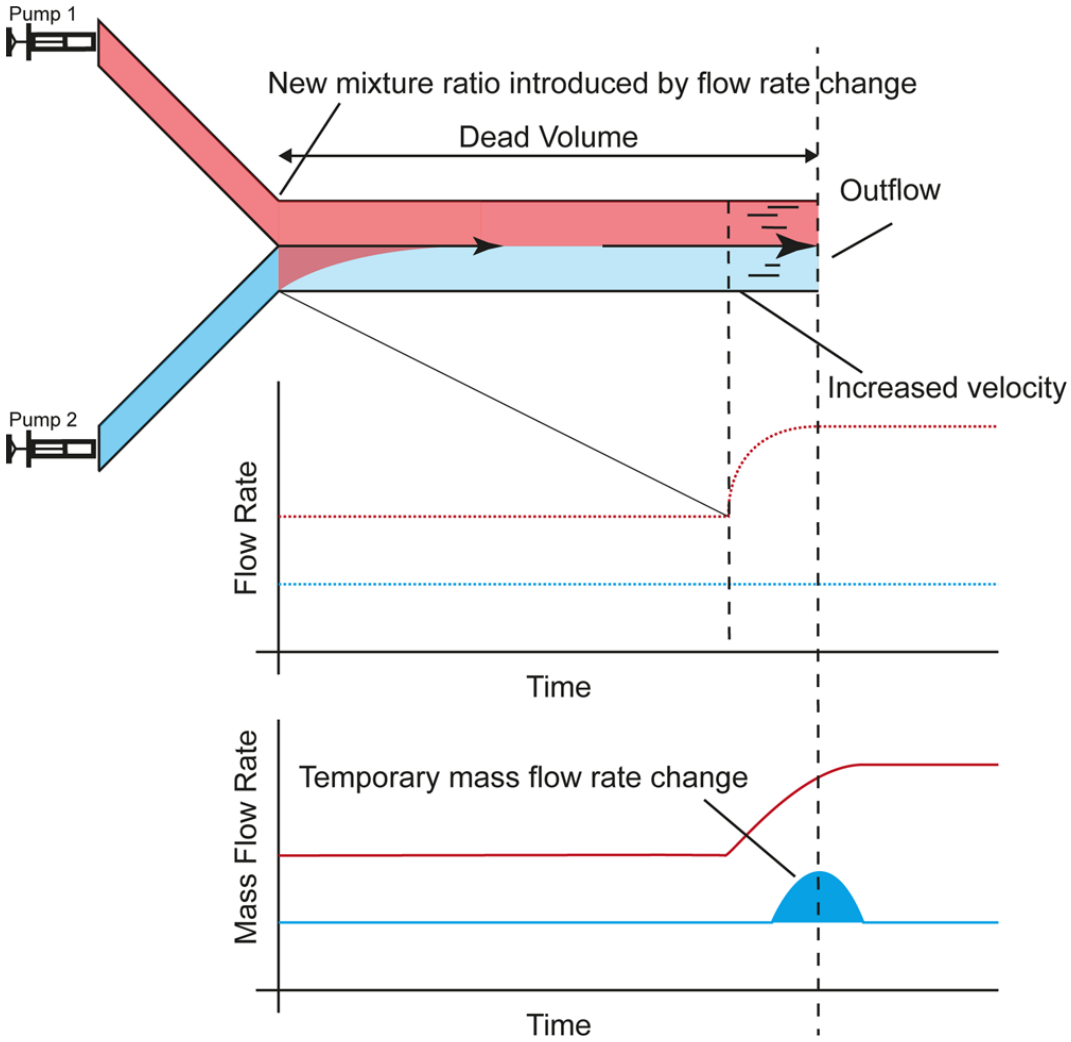

Figure 10 Illustration of dead volume and how that results in a delay of the desired new effective drug outflow or mass flow rate.

Notice that a flow rate increase in one line, leads to a temporary flow rate change in the other infusion line(s). This is because the old concentration is infused at a higher total flow rate.The time it takes for the new concentration rate to arrive at the patient can be estimated with:

$$\Delta t = \frac{Volume}{Flow\ rate} = \frac{\pi l r^2}{\sum_{i=1}^{n} q_i}$$

where l is the distance between the mixture and injection point, r is the internal radius of the infusion line, q_i is the volumetric flow rate of pump i and n is the number of pumps. Disposables that minimize the dead volume reduce the response time and unintended boluses.

The interaction between the pumps is discussed next. Therefore, assume that for one pump the set point is suddenly increased. As discussed earlier, this will result in an increased line pressure. However, because all the lines are connected via the mixing point, the line pressure in the other infusion lines will also increase. As a result of the increased pressure and the compliance, the internal volume of all the infusion lines and accessories will increase. Consequently, the effective outflow of the other infusion lines is temporarily reduced; see Figure 11 for an example.

Note that the effects of dead volume and the interaction between the pumps are opposite:

- An increased flow rate of one pump will result in an *increased dosing rate* due to *dead volume* (the mixture is pushed out faster).
- An increased flow rate of one pump will result in a *decreased dosing* rate due to the *interaction of pumps*.

Because of these opposite effects (temporal) dosing errors are hard to predict. The impact of the interaction between pumps can be reduced by reducing the compliance of the system. Hence, by selecting syringes and infusion lines with a low compliance the interaction between the infusion pumps will be reduced. In Section 3.4.3 it is discussed how the interaction can be predicted.

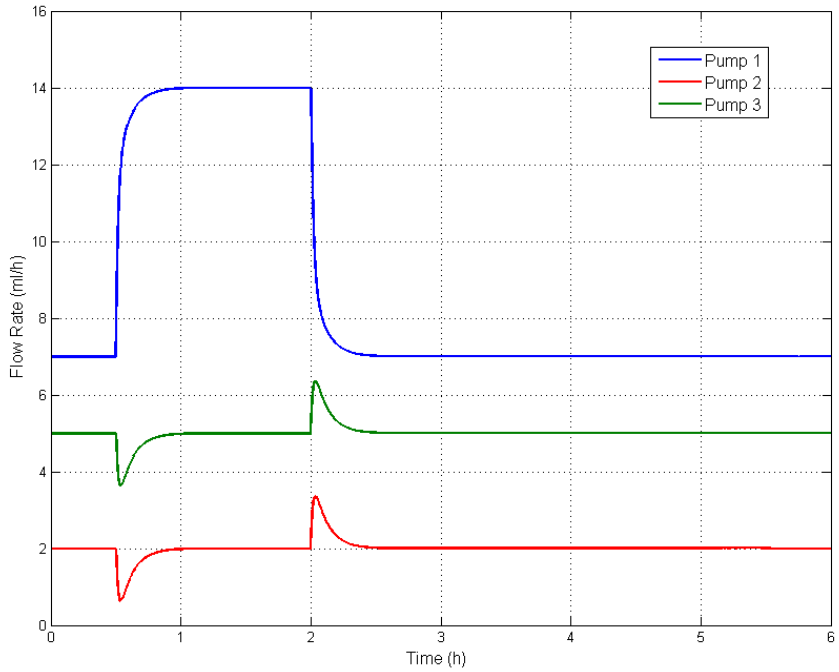

Figure 11 Interaction between pumps resulting in temporal infusion errors. An increase of the infusion rate of pump 1 results in a temporarily decrease in the infusion rates of the other two pumps.

3.4 Testing infusion set ups

In this section it is briefly described how infusion pumps can be tested and characterized.

3.4.1 Startup delay and compliance of infusion set ups

The startup delay of an infusion pump can be directly measured via a calibration set up. It may also be possible to use a master calibrator if it allows for an accurate temporal read out. However, these measurements have to be performed in vitro as the infused liquid has to be collected by a balance or master calibrator. Additionally, it is typically not possible to use a catheter because of the required fluid connections.

An alternative to measure the startup delay is to determine it via a simulation model such as for example developed by UMC Utrecht [4]. This model relies on a relatively simple fluid dynamic model (Hagen–Poiseuille with some alterations) that relates the pressure drop to the infusion line length and diameter. In addition, the model is also capable of measuring the resulting concentration that is administered to the patient considering the dead volume. The compliance, however first has to be

measured or known otherwise. The compliance can be measured in accordance with NEN-EN-ISO 7886-2 or as described in [19].

3.4.2 Dosing error of single pump infusion

To determine the dosing error or flow rate error of an infusion pump it can be calibrated against a flow rate standard, for example a master calibrator such as the Infutest 2000 (Datrend Systems) or the IDA-4/5 (Fluke Biomedical). However, when one relies on a master calibrator, the calibrator itself should also be (periodically) calibrated.

Calibration of syringe pumps are typically performed using a scale with special measures to correct for evaporation and buoyancy. There are written standards [20][21][22] available on how these calibrations should be performed. However, because these calibrations are rather difficult and because the written standards do not include all relevant correction terms for the lowest flow rates, it is recommend to have these calibrations be performed by a high-end calibration laboratory or a National Metrology Institute (NMI).

It is recommended to verify the traceability of the calibrations: even after a sequence of calibrations, there should be a clear link to the highest flow rate standard (developed and maintained by the NMI's). Further, it is recommended that the calibrations are performed for various flow rates in the range of interest. This is important because the flow rate error is typically depended on the flow rate itself. It is also recommended to periodically calibrate the master calibrator to make sure that it does not drift over time.

Calibration of a master calibrator can be performed onsite (at the hospital) or in the laboratory. Hereto a high-end precision syringe is used which has been prior calibrated by an accredited institute. The calibration uncertainty may be slightly larger onsite as the temperature may be less controlled and monitored than what is possible in a dedicated calibration laboratory. The impact of operating conditions can be tested by calibrating the infusion pump at various and possibly varying conditions.

3.4.3 Dosing error multiple pump infusion

It is not trivial to determine the dosing accuracy, or error, when multiple pumps are involved. A possible in vitro method [17], [23] is to add color dyes to the administered drug (or water) and use a spectrometer to determine the concentration of the various 'drugs' after the mixing point. Alternatively one can measure the flow rate of the individual lines with flow meters. However, because of the dead volume effect, the effective outflow concentration will have to be estimated.

An alternative method is to use the same simulation model mentioned in Section 3.4.1. With this model it is possible to predict pump interactions as described in Section 0. However, again the compliance of the various elements needs to be known.

3.5 Summary and recommendations

3.5.1 Response time single pump infusion

The compliance or flexibility in infusion components causes delays in startup and flow rate changes. The startup delay depends on the flow rate, syringe volume, syringe type, accessories and operating

conditions such as back pressure and temperature. Especially items that result in a large compliance (e.g. long infusion line or inclusion of air via a filter) and items that significantly increase the resistance, and thus line pressure, will increase the startup delay. For infusion into veins the startup delays ranges from less than a minute up to several minutes, especially for low flow rates (< 2 ml/h) and large syringe volumes (50 ml).

It is recommended to use relatively rigid infusion components, especially syringes, in order to minimize the startup delay. Furthermore, for low flow rates (< 2 ml/h) it is recommended to use smaller syringe volumes (e.g. 10 ml). Small syringe volumes for large flow rates (> 25 ml/h) should be avoided because this would require a frequent syringe change which increases the risk for an infection. Finally, reducing the internal volume of the accessories reduces the startup time. The volume can for example be reduced by shorter lines or smaller diameters.

3.5.2 Dosing accuracy single pump infusion

For the cases investigated the maximum possible error in the infusion rate was typically below 5% (95% confidence level). In general the lower the flow rate, the larger the maximum possible error and spread in the results. The operating and environmental conditions can impact the flow rate error, however typically this effect is not significant compared to the measurement uncertainty. Sudden changes in backpressure (e.g. height change of pump or infusion bag) have not been studied, however are known to cause a temporarily dosing error.

3.5.3 Dosing accuracy multiple pump infusion

Similarly as for single pump infusion, compliance will result in startup delay for a multiple pump setup. However, for a multiple pump setup also the ‘dead volume’ and ‘interaction between pumps’ will result temporal dosing errors. These effects are typically opposite and therefore counter-intuitive.

It is recommended to use disposables that minimize the dead volume in order to reduce the response time and unintended boluses. Alternatively, one can reduce the length between the mixing and injection point. Furthermore, it is recommended to use low-compliance components to reduce the impact of interacting pumps. Finally, tailored education on this topic is recommended.

3.5.4 Choosing the right setup - general considerations

In this final section some general considerations are given with respect to safe and sound usage of infusion equipment:

- Use as much as possible the recommended syringes and accessories for a particular brand of syringe pump. Typically different syringe makes and models have different diameters which can lead to large infusion errors in case the pump does not correctly identify the syringe. A 5% different inner diameter will lead to an error in flow of more than 10%.

References

[1] T. Sheldon, “Dutch stdy shows that 40% of adverse incidents in hospital are avoidable,” *BMJ.*, vol. 334, no. 1756–1833 (Electronic), p. 925, May 2007.

[2] C. Vincent, P. Aylin, B. D. Franklin, A. Holmes, S. Iskander, A. Jacklin, and K. Moorthy, “Is health care getting safer?,” *BMJ.*, vol. 337, no. 1756–1833 (Electronic), p. a2426, 2008.

[3] J. L. Brady, “First, do no harm: Making infusion pumps safer,” *Biomed. Instrum. Technol.*, vol. 44, no. 5, pp. 372–380, 2010.

[4] P. Lucas, “MeDD - Metrology for drug delivery, EU-funded research project.” [Online]. Available: www.drugmetrology.com.

[5] R. A. Snijder, “MeDD - Survey of best practices,” 2014. [Online]. Available: http://www.drugmetrology.com/bestpract_en/.

[6] J.-L. Vincent, Y. Sakr, C. L. Sprung, V. M. Ranieri, K. Reinhart, H. Gerlach, R. Moreno, J. Carlet, J.-R. Le Gall, and D. Payen, “Sepsis in European intensive care units: results of the SOAP study.,” *Crit. Care Med.*, vol. 34, no. 2, pp. 344–353, 2006.

[7] A. L. C. Minderhoud and U. Utrecht, “Reiniging en desinfectie - beleid.” 2014.

[8] NVZA, V&VN, and WIP, “Richtlijn Voor Toediening Gereed Maken (VTGM).” [Online]. Available: http://www.vmszorg.nl/_library/5529/VGTM_richtlijn_nov2009.pdf.

[9] M. P. H. van den Broek and U. Utrecht, “Extravasatieprotocol voor artsen en verpleegkundigen.” 2015.

[10] U. Utrecht, “Handboek Parenteralia.” .

[11] P. W. Abbel, O., Griffioen, J., Raaijmakers, C.P.J., Timmerman, A.M.D., Vermeulen-2 and U. Utrecht, “Incidentmanagement medische hulpmiddelen,” 2015.

[12] N. Schmidt, C. Saez, I. Seri, and A. Maturana, “Impact of syringe size on the performance of infusion pumps at low flow rates,” *Pediatr.Crit.Care Med*, vol. 11, no. 2, pp. 282–286, Mar. 2010.

[13] S. B. Neff, T. A. Neff, S. Gerber, and M. M. Weiss, “Flow rate, syringe size and architecture are critical to start-up performance of syringe pumps,” *Eur.J.Anaesthesiol.*, vol. 24, no. 0265–0215 (Print), pp. 602–608, Jul. 2007.

[14] N. Schmidt, C. Saez, I. Seri, and A. Maturana, “Impact of syringe size on the performance of infusion pumps at low flow rates,” *Pediatr.Crit Care Med.*, vol. 11, no. 1529–7535 (Print), pp. 282–286, Mar. 2010.

[15] D. Neal and J. A. Lin, “The effect of syringe size on reliability and safety of low-flow infusions,” *Pediatr. Crit. Care Med.*, vol. 10, no. 5, pp. 592–596, 2009.

[16] D. W. Kim and D. J. Steward, “The effect of syringe size on the performance of an infusion pump,” *Paediatr. Anaesth.*, vol. 9, no. 4, pp. 335–337, 1999.

[17] R. A. Snijder, M. K. Konings, P. Lucas, T. C. Egberts, and A. M. Timmerman, “Flow variability and its physical causes in infusion technology: a systematic review of in vitro measurement and modeling studies, revision submitted,” *Biomed. Eng. / Biomed. Tech.*, 2015.

[18] B.braun, “Infusomat®, Volumetric pump and Perfusor® Space.” [Online]. Available: http://www.space.bbraun.com/documents/Space_System_Technical_Data_l.pdf.

[19] E. Batista, N. Almeida, A. Furtado, E. Filipe, L. Souse, M. Rui, L. Peter, H. T. Petter, R. Snijder, and A. Timmerman, “Assessment of drug delivery devices,” *Biomed. Eng. / Biomed. Tech. Accept.*, 2015.

[20] *ISO 7886-2 Sterile hypodermic syringes for single use – Part 2: Syringes for use with power-driven syringe Pump-International*. 2011.

[21] *ISO 28620:2010 Medical devices -- Non-electrically driven portable infusion devices*. 2015.

[22] *IEC, IEC 60601-2-24 (1998). Medical electrical equipment - Part 2-24: Particular requirements for the safety of infusion pumps and controllers, Switzerland*. 1998.

[23] A. M. Timmerman, R. A. Snijder, P. Lucas, M. C. Lagerweij, J. H. Radermacher, and M. K. Konings, “How infusion system physical parameters cause clinically relevant dose deviations at setpoint changes, revision submitted,” *Biomed. Eng. / Biomed. Tech.*, 2015.